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Measurement of Azimuthal Asymmetries in Inclusive Production of Hadron Pairs in e^+e^- Annihilation at Belle

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The Collins effect connects transverse quark spin with a measurable azimuthal dependence in the yield of hadronic fragments around the quark's momentum vector. Using two different reconstruction methods we find evidence of statistically significant azimuthal asymmetries for charged pion pairs in e^+e^- annihilation at a center-of-mass energy of 10.52 GeV, which can be attributed to a transverse polarization of the primordial quarks. The measurement was performed using a sample of 79 million hadronic events collected with the Belle detector.

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The relationship between quark spin and the properties of hadrons is still poorly understood. In the fragmentation of a quark into hadrons, Collins [1] has proposed a relation between transverse quark spin and the final state azimuthal distribution of hadrons around the original quark momentum direction. Azimuthal asymmetries of hadron yields have recently been reported in deep inelastic scattering off transversely polarized hydrogen [2] and deuteron [3] targets: these are believed to be due to the product of Collins fragmentation functions and transverse quark spin distribution functions in the nucleon. However, these so-called transversity distributions, which contribute to the nucleon transverse spin, have not been independently measured. Similarly, no measurement of Collins fragmentation functions has yet been reported.

In this Letter we present a measurement of azimuthal asymmetries in hadron-hadron correlations for inclusive charged dihadron production $e^+e^- \rightarrow hhX$, which we interpret as a direct measure of the Collins effect. Exploratory studies for this measurement were reported in [4]. This analysis was performed using a sample of 79 million events ($29\,\mathrm{fb}^{-1}$) collected at a center-of-mass system (CMS) energy 60 MeV below the $\Upsilon(4S)$ resonance with the Belle detector [5] at the KEKB asymmetric-energy e^+e^- storage rings [6]. For systematic checks, Monte Carlo (MC) simulated events generated by the QQ and JETSET [7] packages and processed with a full GEANT-based [8] simulation of the Belle detector were used.

The Collins effect occurs in the fragmentation of a quark q with transverse spin $\mathbf{S_q}$ and 3-momentum $\mathbf{k}$ into an unpolarized hadron h with transverse momentum $\mathbf{P}_{h\perp}$ with respect to the original quark direction. The corresponding number density is defined as [9]

$$D_{hq^\uparrow}(z,\mathbf{P_{h\perp}}) = D_1^q(z,P_{h\perp}^2)+H_1^{\perp q}(z,P_{h\perp}^2)\frac{(\hat{\mathbf{k}}\times\mathbf{P}_{h\perp})\cdot\mathbf{S}_q}{zM_h}, \tag{1}$$

where $z=\frac{2E_h}{Q}$ is the fractional energy of the hadron relative to half of the CMS energy Q. The first term describes the spin averaged fragmentation function (FF), and the second, containing the Collins function $H_1^{\perp q}(z,P_{h\perp}^2)$, depends on the spin of the quark and produces an asymmetry as it changes sign if $\mathbf{S_q}$ flips. The vector product leads to a $\sin(\phi)$ modulation, where ϕ is the azimuthal angle between the plane spanned by the hadron and quark momenta, and the plane spanned by the quark momentum and the incoming leptons. Experimentally the quark direction is approximated by the thrust axis $\hat{\mathbf{n}}$.

In hadron production in $e^+e^- \rightarrow q\bar{q}$ events, the Collins effect can be observed when the fragments of the quark and anti-quark are considered simultaneously. Combining two hadrons from different hemispheres in jet-like events, with azimuthal angles ϕ_1 and ϕ_2 as defined in Fig. 1 (note that all angular vairablels as well as $\vec{n}$ are defined in the CMS), produces a $\cos(\phi_1+\phi_2)$ modulation of the di-hadron yield. A MC comparison of thrust axis cal-

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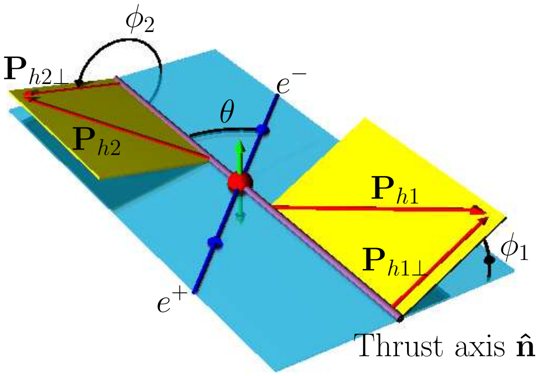

FIG. 1: Definition of the azimuthal angles of the two hadrons. In each case, ϕ_i is the angle between the plane spanned by the lepton momenta and the thrust axis $\hat{n}$, and the plane spanned by $\hat{n}$ and the hadron transverse momentum $P_{hi\perp}$.

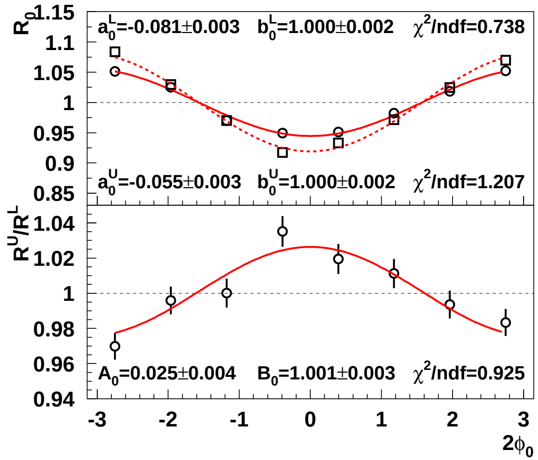

FIG. 2: Top: Unlike(U)-sign and like(L)-sign pion pair normalized rate R_0 vs. $2\phi_0$ in the bin $z_1(z_2) \in [0.5, 0.7]$, $z_2(z_1) \in [0.3, 0.5]$. Bottom: Pion pair double ratio R_0^U/R_0^L vs. $2\phi_0$ in the same bin. The solid and slashed lines show the results of the fit described in the text.

culations using reconstructed and generated tracks shows an average angular deviation between the two of 75 mrad, with a spread with root mean square of 74 mrad. This smearing of the reconstructed axis leads to a reduction in the measured azimuthal asymmetry, as discussed below.

Two experimental methods are used to measure azimuthal asymmetries. The first method (M_{12}) gives rise to the $\cos(\phi_1 + \phi_2)$ modulation in the di-hadron yields. The yield is recorded as a function of the hadron angle sum $\phi_1+\phi_2$, $N_{12} = N_{12}(\phi_1+\phi_2)$, and divided by the average yield to obtain the normalized rate $R_{12} := N_{12}(\phi_1 + \phi_2)/\langle N_{12}\rangle$, parametrized by $R_{12} = a_{12}\cos(\phi_1+\phi_2)+b_{12}$. Here, a_{12} is a function of the first moment ($H_1^{\perp q,[1]}$) of the Collins function [10]

$$a_{12}(\theta, z_1, z_2) = \frac{\sin^2\theta}{1+\cos^2\theta}\frac{H_1^{\perp q,[1]}(z_1)\overline{H}_1^{\perp q,[1]}(z_2)}{D_1^q(z_1)\overline{D}_1^q(z_2)}, \quad (2)$$

where θ is the angle between the incoming lepton axis and the thrust axis. An alternative method (M_0) does not rely on knowledge of the thrust axis: yields are measured as a function of ϕ_0, the angle between the plane spanned by the momentum vector of the first hadron and the lepton momenta, and the plane defined by the two hadron momenta. The corresponding normalized rate $R_0 = N_0(2\phi_0)/\langle N_0\rangle$ is a function of $\cos(2\phi_0)$, and (following [11]) can be parametrized as $a_0\cos(2\phi_0)+b_0$ with

$$a_0(\theta_2, z_1, z_2) = \frac{\sin^2\theta_2}{1+\cos^2\theta_2}\frac{f\left(H_1^{\perp q}(z_1)\overline{H}_1^{\perp q}(z_2)/M_1M_2\right)}{D_1^q(z_1)\overline{D}_1^q(z_2)}\ . \quad (3)$$

f denotes convolution over the transverse hadron momenta. M_1 and M_2 are the masses of the two hadrons, z_1 and z_2 are their fractional energies and θ_2 is the angle between the beam axis and the second hadron momentum. The $\sin\theta_2$ dependence reflects the probability of finding the two initial quarks with transverse spin. $\overline{D}_1^q(z)$ and $\overline{H}_1^{\perp q}$ denote fragmentation functions for anti-quarks.

To reduce hard gluon radiation, a two-jet-like topology is enforced by requiring a thrust value $T > 0.8$, calculated from all charged and neutral particles with momentum exceeding 0.1 GeV/c. The following selection criteria were imposed on the charged pions used in the analysis methods M_{12} and M_0: (1) Tracks are required to originate from the collision vertex, and to lie in a fiducial region $-0.6 < \cos(\theta_{\rm lab}) < 0.9$, where $\theta_{\rm lab}$ is the polar angle in the laboratory frame. (2) A likelihood ratio is used to separate pions from kaons [5]: $\mathcal{L}(\pi)/[\mathcal{L}(K)+\mathcal{L}(\pi)] > 0.7$. MC studies show that less than 10% of pairs have at least one particle misidentified. (3) We require $z_1, z_2 > 0.2$, to reduce decay contributions to the pion yields. In addition we require the visible energy in the detector to exceed 7 GeV. (4a) The tracks must lie in opposite jet-hemispheres: $(\mathbf{P}_{h1}\cdot\hat{\mathbf{n}})(\mathbf{P}_{h2}\cdot\hat{\mathbf{n}}) < 0$. (4b) Q_T is the transverse momentum of the virtual photon from the e^+e^- annihilation in the rest frame of the hadron pair [11]. We require $Q_T < 3.5$ GeV/c, which removes contributions from hadrons assigned to the wrong hemisphere.

The analysis is performed in (z_1, z_2) bins with boundaries at $z_i = 0.2$, 0.3, 0.5, 0.7 and 1.0, where complementary off-diagonal bins (z_1, z_2) and (z_2, z_1) are combined. In each (z_1, z_2) bin, normalized rates R_{12} and R_0 are evaluated in 8 bins of constant width in the angles $\phi_1+\phi_2$ and $2\phi_0$ respectively, and fitted with the functional form introduced above. Results in the lowest (z_1, z_2) bin are shown in Fig. 2. In both methods the constant term (b_{12} or b_0) is found to be consistent with unity for all bins.

In addition to their sensitivity to the Collins effect, R_{12} and R_0 have contributions from instrumental effects and QCD radiative processes: these are charge independent,

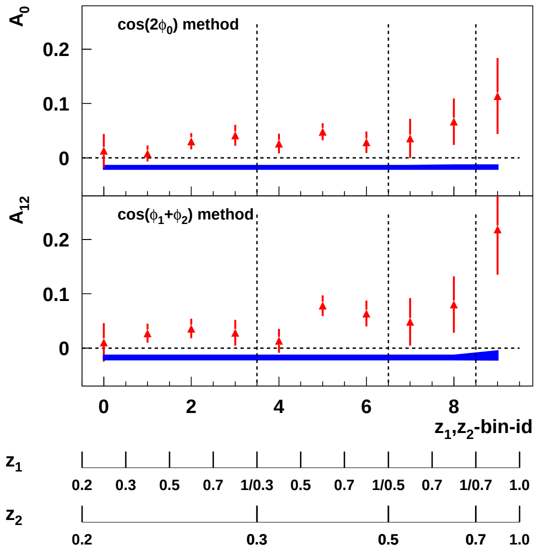

FIG. 3: Values of A_0 and A_{12} as functions of z, corrected for the contribution of charm events. The lower scales show the boundaries of the bins in z_1 and z_2; see the text. The shaded band shows the size of the systematic errors.

and cancel in the double ratio of normalized rates for unlike-sign(U) over like-sign(L) pion pairs,

$$\frac{R^U_\alpha}{R^L_\alpha} := \frac{N^U_\alpha(\beta_\alpha)/\langle N^U_\alpha\rangle}{N^L_\alpha(\beta_\alpha)/\langle N^L_\alpha\rangle},$$
$$\alpha = 0, 12, \quad \beta_0 = 2\phi_0, \quad \beta_{12} = \phi_1 + \phi_2. \tag{4}$$

In linear approximation the double ratio is proportional to a combination of the favored and disfavored fragmentation functions: omitting the transverse momentum dependence,

$$\begin{aligned} R^U_0/R^L_0 &= 1 + \cos(2\phi_0)\frac{\sin^2\theta}{1+cos^2\theta} \\ &\times\Bigg\{\frac{f\left(H_1^{\perp,fav}\overline{H}_1^{\perp,fav} + H_1^{\perp,dis}\overline{H}_1^{\perp,dis}\right)}{\left(D_1^{fav}\overline{D}_1^{fav} + D_1^{dis}\overline{D}_1^{dis}\right)} \\ &-\frac{f\left(H_1^{\perp,fav}\overline{H}_1^{\perp,dis}\right)}{\left(D_1^{fav}\overline{D}_1^{dis}\right)}\Bigg\}; \end{aligned} \tag{5}$$

an analogous expression can be given for R^U_{12}/R^L_{12}. Favored fragmentation processes (*e.g.* D_1^{fav}) are transitions in which a valence quark of the hadron is of the same flavor as the initial quark, for example $u, \bar{d} \to \pi^+$; the corresponding unfavored process is $u, \bar{d} \to \pi^-$. Following our analysis of the normalized rates we parametrize the double ratios as $R^U_\alpha/R^L_\alpha = A_\alpha\cos(\beta_\alpha) + B_\alpha$ with $\alpha = 0, 12$, $\beta_0 = 2\phi_0$ and $\beta_{12} = \phi_1 + \phi_2$; the parameters A_α, B_α are determined from fits in each (z_1, z_2)-bin.

An example is shown in Fig. 2. The parameters A_0 and A_{12}, related to the Collins fragmentation functions (see Eq. 5), are shown in Fig. 3 and listed in Table I. Significant non-zero values are observed, especially at high z. The observed increase with z is predicted in several models [12, 13, 14]. The weighted averages over all (z_1, z_2)-bins, corrected for the charm contribution (see below), are found to be $A_0 = (3.06 \pm 0.65 \pm 0.55)\%$ and $A_{12} = (4.26 \pm 0.78 \pm 0.68)\%$[15].

By measuring asymmetries using double ratios, acceptance effects cancel, while the contribution of gluon radiation cancels only to first order. The size of any additional contribution was estimated by subtracting like-sign from unlike-sign pair rates, in which case gluon effects should cancel exactly and only experimental effects should remain. The differences, 0.04% on average for method M_0 and 0.03% for M_{12}, are assigned as systematic errors. Double ratios were formed using MC events, which do not include the Collins effect but take into account gluon radiation and detector effects: the parameters A_0 and A_{12} were found to be consistent with zero. The statistical errors of these fits, 0.45% and 0.56% respectively, are included in the systematic uncertainty. Double ratios of positively-charged over negatively-charged pairs were found to be consistent with unity, and limit the possibility of charge dependent detector effects; again, the precisions of the fits (0.26% and 0.21%) are included as systematic errors. An additional test was performed by taking pion pairs from jet hemispheres in different events: no asymmetry was found.

In addition to fitting the double ratios with a $\cos\phi$ modulation, higher harmonics ($\sin 2\phi, \cos 4\phi$) were introduced. The change in the results, 0.03% on average for A_0 and 0.01% for A_{12}, was included in the systematic uncertainty. In method M_{12}, the single hadron yield around the thrust axis was also studied. Although the Collins effect leads to a sinusoidal modulation, this should average to zero in the absence of a specified quark spin. The $\sin\phi_{1,2}$ modulation was found to be consistent with zero.

As a consistency check, we also measure double ratios from an event sample with a reversed thrust selection, $T < 0.8$: asymmetries in this sample are reduced for $Q_T < 3.5$ GeV/c (see Fig. 4). For the low-thrust sample there is no clear two-jet topology, and, thus, the Collins effect should be suppressed while any radiative or acceptance effects remain present. A fit to a constant for $Q_T < 3.5$ GeV/c finds $(0.4 \pm 0.3)\%$ for both A_0 and A_{12}. The asymmetries for $Q_T > 3.5$ GeV/c and $T < 0.8$ were found to be due to events with low visible energy as well as background from interactions in the detector material.

The uncertainty due to particle misidentification was estimated by applying tighter selection criteria. The difference in the double ratio with respect to the default selection is included in the systematic error, 0.12% for method M_0 and 0.28% for M_{12}.

To test the reconstruction of azimuthal asymmetries, Monte Carlo samples were reweighted in $\cos(2\phi_0)$ and $\cos(\phi_1 + \phi_2)$, producing generated moments of 5% and

TABLE I: A_0 and A_{12} values obtained from fits to pion double ratios as a function of z. The errors shown are statistical and systematic.

$z_1 \leftrightarrow z_2$		A_0	A_{12}
[0.2, 0.3]	[0.2, 0.3]	$(1.68 \pm 3.10 \pm 0.54)\%$	$(1.08 \pm 3.53 \pm 0.67)\%$
[0.2, 0.3]	[0.3, 0.5]	$(0.77 \pm 1.46 \pm 0.54)\%$	$(2.74 \pm 1.76 \pm 0.67)\%$
[0.2, 0.3]	[0.5, 0.7]	$(3.36 \pm 1.49 \pm 0.54)\%$	$(3.60 \pm 1.80 \pm 0.67)\%$
[0.2, 0.3]	[0.7, 1.0]	$(4.10 \pm 1.95 \pm 0.54)\%$	$(2.84 \pm 2.37 \pm 0.67)\%$
[0.3, 0.5]	[0.3, 0.5]	$(2.71 \pm 1.82 \pm 0.54)\%$	$(1.34 \pm 2.21 \pm 0.67)\%$
[0.3, 0.5]	[0.5, 0.7]	$(5.19 \pm 1.56 \pm 0.54)\%$	$(7.82 \pm 1.88 \pm 0.67)\%$
[0.3, 0.5]	[0.7, 1.0]	$(3.28 \pm 1.98 \pm 0.56)\%$	$(6.37 \pm 2.37 \pm 0.67)\%$
[0.5, 0.7]	[0.5, 0.7]	$(4.01 \pm 3.59 \pm 0.55)\%$	$(4.84 \pm 4.37 \pm 0.67)\%$
[0.5, 0.7]	[0.7, 1.0]	$(5.24 \pm 4.26 \pm 0.62)\%$	$(8.02 \pm 5.19 \pm 0.70)\%$
[0.7, 1.0]	[0.7, 1.0]	$(12.78 \pm 6.98 \pm 0.62)\%$	$(21.84 \pm 8.34 \pm 1.59)\%$

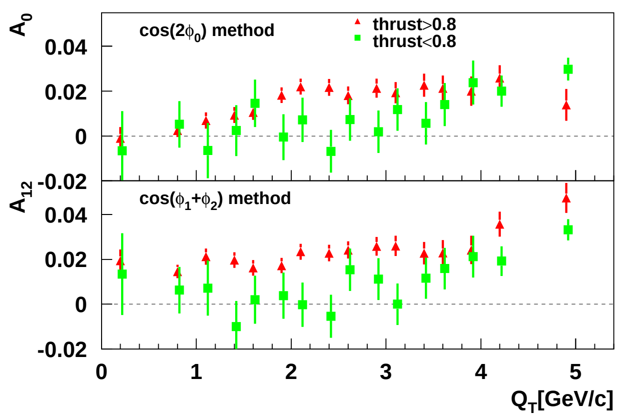

FIG. 4: Values of A_0 and A_{12} as a function of Q_T (not corrected for charm background) for the data samples with $T > 0.8$ (triangles) and $T < 0.8$ (squares).

10% for unlike-sign pairs, and 0% and −5% for like-sign pairs. The reconstructed azimuthal asymmetries were consistent with generated values for method M_0, but lower by $17.6 \pm 1.1\%$ on average for method M_{12}, which depends on the thrust axis of the reconstructed event. (Note that the thrust axis represents the direction of the outgoing quarks only on average.) This dilution was corrected by rescaling A_{12} with a factor 1.210 ± 0.014.

Both methods depend on the assumption that the electron and positron beams are unpolarized. This was tested by studying the angular distribution of $e^+e^- \to \mu^+\mu^-$ events: no significant azimuthal asymmetries are observed and thus no systematic error assigned to it. We correct for the contribution from charm decays using measured asymmetries in events where a D^* meson has been reconstructed, and the $e^+e^- \to c\bar{c}$ event fraction determined from MC (23%). The corresponding uncertainty is included in the statistical errors in Table I. The fraction of selected events due to the $e^+e^- \to \tau^+\tau^-$ process is small (1.7%), and the asymmetries obtained in a tau enhanced data sample have low statistical significance: $A_0 = (0.17 \pm 0.30)\%$ and $A_{12} = (0.74 \pm 0.30)\%$. This contribution is added to the systematic error. All systematic uncertainties were added in quadrature. Correlations among individual angular and (z_1, z_2)-bins were tested using a large number of MC samples, by comparing uncertainties returned by the fits with the expected values. We find the statistical error to be underestimated by 14%; the final uncertainty is increased by the corresponding factor.

In summary we have performed a measurement of the azimuthal asymmetry in the inclusive production of pion pairs as a function of the fractional energy z of pion pairs. In the double ratio of asymmetries from unlike-sign and like-sign pairs, possible contributions of gluon radiation and detector effects cancel and the observed asymmetry can be attributed to the Collins effect. This asymmetry in e^+e^- annihilation is the first direct evidence for this effect.

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